NOTES ON METAMORPHIC AND PLUTONIC ROCKS AND THEIR BIOTITES FROM THE WANTABADGERY–ADELONG–TUMBARUMBA DISTRICT, N.S.W.

By T. G. VALLANCE.

(Four Text-figures.)

[Read 30th March, 1960.]

Synopsis.

Variations in the chemical composition of biotites from pelitic rocks belonging to a metamorphic sequence of the Buchan type are related to the bulk composition and the nature of the ferromagnesian phases occurring with the biotites. With increase in metamorphic grade there is a decrease in the ratio $Fe_2O_3/Fe_2O_3 + FeO$ of both host rocks and biotites; the low-grade biotite is especially rich in ferric iron. Development of cordierite involves a change in the Fe/Mg ratio of the associated biotites. The biotites from plutonic rocks associated with the metamorphic sequence are generally similar in composition to those of the higher-grade metasediments.

INTRODUCTION.

H. H. Read (1952) has drawn attention to two contrasted regional metamorphic zonal sequences observable in the Dalradian pelitic rocks of eastern Scotland. The first of these, the so-called Barrovian sequence, to be seen in the Deeside area of Aberdeenshire, consists of chlorite, biotite, almandine, staurolite, kyanite and sillimanite zones (Barrow (1912), with modifications by Tilley (1925)) in order of increasing metamorphic intensity. Further north in Aberdeenshire and in Banffshire, rocks of generally similar chemical composition to those of Deeside are marked by the development of andalusite and cordierite at intermediate to high metamorphic grades and by the rarity or absence of almandine, staurolite and kyanite. This second type of association has been called the Buchan type by Read. The two types are believed to represent differences in the physical conditions of metamorphism. Examples of both Buchan and Barrovian patterns have been recorded from various parts of the world; no doubt there are also instances with characters gradational between the two contrasted patterns. In Japan, Miyashiro (1958) has used the term Central Abukuma type in referring to an association similar to that in the Buchan type of metamorphism.

A belt of rocks, showing signs of a Buchan type of metamorphism, and associated with various granitic bodies, extends for a distance in excess of 200 miles from north-eastern Victoria into southern New South Wales. Howitt (1888) and Tattam (1929) have described rocks from the Victorian end of the belt. In New South Wales metamorphic zones have been mapped and described in the Albury district by Joplin (1947) and in the Wantabadgery-Adelong-Tumbarumba district, east and south-east of Wagga Wagga, by Vallance (1953*a*). East of this main belt, similar rocks occur at Cooma, N.S.W.; these were studied in detail by Joplin (1942).

In the Wantabadgery-Adelong-Tumbarumba area, aluminous pelites and sandier rocks (originally subgreywackes and related siltstones) are associated with granitic masses belonging to two main age groups. Variations in metamorphic intensity have been plotted by means of isograds delimiting the following zones: (1) low-grade zone, (2) biotite zone, (3) knotted schist zone, and (4) high-grade zone. Increase in metamorphic grade occurs in the field with approach to the Wantabadgery Granite or the Green Hills Granite which together constitute the older granite group. Rocks of the low-grade zone typically contain a colourless to very pale green mica and chlorite. With increase in grade the phyllites and fine mica-schists acquire brown biotite at the expense of chlorite and the pale mica and thus pass into the biotite zone. At a more advanced grade, colourless andalusite and some cordierite porphyroblasts are developed in the pelites which become knotted schists. In the highest-grade zone the metasediments may have little or no schistosity. These rocks have been termed spotted

granulites, following Joplin (1942, p. 175). The spotted granulites contain such minerals as sillimanite, pink pleochroic andalusite, cordierite, oligoclase and sometimes potash feldspar. Reddish-brown biotite is found in most of the metasediments from within, or of a higher grade than, the biotite zone. At the metamorphic "peak" biotite may be replaced by sillimanite. Muscovite is present in all grades, but it is clearly not of a single generation; in some high-grade rocks fine muscovite replaces sillimanite. The high-grade zone has a maximum width in outcrop of from four to five miles, but in some places is very restricted in extent. The width of the knotted schist zone is also variable. Garnets (both almandine and spessartine), staurolite and kyanite are absent from the metasediments of the present area.

In terms of the scheme of facies outlined by Fyfe, Turner and Verhoogen (1958), the mineral associations in the present metamorphic succession are much more like those of the "facies of contact metamorphism" than those of the "facies of regional metamorphism". The Barrovian metamorphic sequence falls within the "facies of regional metamorphism" while the Buchan type of regional metamorphism is considered with the "facies of contact metamorphism" by Fyfe, Turner and Verhoogen. Unfortunately the terminology may appear somewhat misleading. Both types of metamorphism discussed here are regional in extent, but, whereas the Barrovian association includes pelitic mineral assemblages "characteristic" of regional meta-morphism, the mineral assemblages of pelites in the Buchan type of metamorphism are similar to those of pelites in contact thermal aureoles. It should be emphasized, however, that the fabrics of rocks in a Buchan-type sequence are quite different from the typical hornfels fabrics found in many contact aureoles. There need be little real ambiguity in the matter if it is recognized that the two groups of facies simply represent different sets of physical conditions between which a complete gradation exists. Whether or not the Buchan type of metamorphism is truly a reflection of contact metamorphism related to intrusive bodies is a matter open to question. The writer prefers to consider the older granites and the metamorphism of the sedimentary rocks of the present area as related genetically, with the granitic rocks representing a product rather than a cause of the metamorphism (Vallance, 1953b). The association of potash feldspar with sillimanite or andalusite in apparent equilibrium in the high-grade rocks of this area suggests an approach to Pyroxene Hornfels Facies conditions at the higher-grade end of the metamorphic series. At the low-grade end, pelitic rocks contain mineral assemblages typical of the Greenschist Facies. There is no evidence of a Zeolite Facies (Fyfe, Turner and Verhoogen, 1958) in the region, even in rocks (metamorphosed intermediate-basic igneous rocks) the composition of which would be favourable to the development of zeolites at appropriate grades.

Whilst our knowledge of the chemical compositions of biotites in plutonic rocks is fairly extensive, chemical information concerning biotites of pelitic schists is most limited. The main reason for this deficiency is, no doubt, connected with the mechanical difficulties involved in preparing pure concentrates of pelitic biotites. In 1893, Barrow published a partial analysis of a biotite from a metasediment collected in Deeside. Snelling (1957) gives analyses of six biotites also from Deeside. Barth (1936) analysed two biotites from metasediments of Dutchess County, New York. These data refer to biotites from Barrovian sequences. Miyashiro (1958) and Shidô (1958) have analysed pelitic biotites from Buchan-type metamorphic sequences. No data are available on the pelitic biotites from Banffshire.

DATA AND DISCUSSION.

Three of the analysed biotites discussed here are from metamorphosed pelites, one is from a sample of a granite and one from a biotite-rich inclusion (probably of sedimentary origin) in the granite body. The biotites were concentrated by gravity methods involving first a rough separation using bromoform followed by centrifuging in methylene iodide. Each concentrate, after several centrifugings, was checked finally with the aid of a binocular microscope. The biotite samples and the host rocks were

TABLE 1.

	1 Rock	1 Biotite	2 Rock	2 Biotite	3 Rock	3 Biotite	4 Rock	4 Biotite	5 Rock	5 Biotite
SiO_2	56·74	36·64	56·28	36·72	54·01	34·67	54·86	34·58	72·53	35·81
Al_2O_3	23·11	20·54	23·02	18·86	24·41	19·54	18·32	19·05	14·57	19·48
TiO_2	0·56	1·16	0·77	2·63	0·85	3·63	1·18	2·96	0·42	3·10
Fe_2O_3	3·73	9·82	1·82	4·01	1·39	3·76	2·01	3·48	0·74	3·93
FeO	2·98	10·18	5·84	16·56	5·95	17·96	8·01	17·25	2·02	16·65
MnO	0·04	0·12	0·06	0·13	0·07	0·23	0·14	0·65	0·04	0·22
MgO	2·46	8·10	3·28	8·42	2·91	8·17	4·16	9·09	1·04	7·34
CaO	0·21	0·10	0·14	0·24	0·36	0·26	1·95	0·42	0·70	0·42
Na_2O	0·21	0·25	1·21	0·61	1·09	0·38	2·46	0·79	2·25	0·54
K_2O	6·39	8·43	4·97	7·51	5·45	7·63	5·22	8·41	4·96	8·69
H_2O^+	3·30	4·11	2·82	3·91	2·64	3·67	1·30	3·07	0·72	3·50
H_2O^-	0·53	0·45	0·24	0·52	0·28	0·58	0·22	0·66	0·11	0·37
P_2O_5	n.d.	n.d.	0·10	n.d.	0·15	n.d.	n.d.	n.d.	0·09	0·19
Total ..	100·26	99·90	100·55	100·12	99·56	100·48	99·83	100·41	100·19	100·05
mg	0·41	0·43	0·44	0·43	0·42	0·41	0·43	0·44	0·41	0·39
Fe_2O_3/Fe_2O_3+FeO	0·56	0·49	0·23	0·20	0·19	0·17	0·20	0·17	0·27	0·19

Key.

1. Biotite-muscovite-quartz phyllite (with accessory iron-oxide minerals).
   Loc.: Por. 45, Par. Borambula, Co. Wynyard.
2. Knotted schist (biotite-muscovite-andalusite-cordierite-quartz).
   Loc.: Por. 65, Par. Yabtree, Co. Wynyard.
3. Spotted granulite (biotite-muscovite-andalusite-cordierite-quartz-oligoclase-K feldspar-sillimanite (minor)).
   Loc.: Por. 32, Par. Wallace, Co. Wynyard.
4. Inclusion (biotite-oligoclase-muscovite-quartz-sillimanite-K feldspar) in granodiorite.
   Loc.: Por. 218, Par. Tenandra, Co. Clarendon.
5. Biotite granite (quartz-K feldspar-oligoclase-biotite-muscovite-sillimanite (minor)).
   Loc.: Por. 235, Par. Oura, Co. Clarendon.
   Anal.: T.G.V.

Biotite Cations : 24 (O, OH, F)

		1	2	3	4	5
Z	Si	5·411	5·494	5·243	5·303	5·427
	Al	2·589	2·506	2·757	2·697	2·573
	Al	0·988	0·818	0·726	0·745	0·906
	Ti	0·129	0·296	0·413	0·341	0·352
Y	Fe^{+++}	1·090	0·451	0·427	0·400	0·448
	Fe^{++}	1·257	2·071	2·271	2·211	2·110
	Mn	0·014	0·016	0·029	0·084	0·028
	Mg	1·782	1·877	1·841	2·077	1·658
X	Ca	0·015	0·038	0·042	0·068	0·067
	Na	0·071	0·176	0·111	0·234	0·159
	K	1·587	1·433	1·470	1·644	1·679
	OH	4·049	3·902	3·702	3·142	3·537

Optical Data :

	1	2	3	4	5
X ..	Pale greenish-yellow.	Pale straw-yellow.	Pale straw.	Pale straw.	X .. Pale straw-brown.
Y ..	Brown, slightly greenish.	Medium reddish-brown.	Dark reddish-brown.	Dark reddish-brown.	Y .. Reddish-brown.
Z ..	Brown, slightly greenish.	Medium reddish-brown.	Dark reddish-brown.	Dark reddish-brown.	Z .. Reddish-brown.
α ..	—	1·595	1·598	1·600	1·603
β ..	—	1·638	1·643	1·644	1·649
γ ..	1·665	1·638	1·644	1·645	1·651

analysed according to the standard methods of Groves (1951) with the exception that alkalis in rock (1) and biotite (1) were estimated by means of flame photometry and that combined water in all cases was determined by the Penfield method. Analytical results and appropriate optical information are collected in Table 1.

Biotites from the Metamorphic Zonal Sequence.

Biotite (1) is from a fine-grained buff-coloured phyllitic rock not far inside the biotite isograd. In this area brown or greenish-brown biotite usually appears first in the sandier rocks and there is often a distinct lag before it develops in the pelites. As indicated above, biotite apparently forms at the expense of chlorite and muscovite. The reaction may involve the conversion of an antigoritic chlorite to an amesitic chlorite, though little is known of the chlorites in this succession. Chlorite often does not persist far into the biotite zone. With increase in grade the biotite becomes reddish-brown in colour and the next sample (2) from a dark-brown knotted schist is of this colour. The knotted schist contains a few relict grains of andalusite, but most of the porphyroblasts have been converted to fine white mica. Biotite (3) is from a spotted granulite well within the high-grade zone. In this case fresh andalusite is common; unaltered cordierite is also present, but typically this mineral has been replaced by micaceous aggregates. Muscovite is present in each of the analysed rocks.
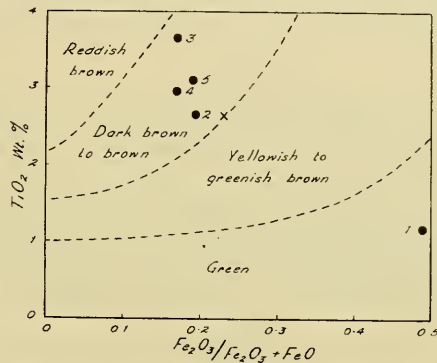

Figure 1. Diagram based on Hayama's (1959) chart showing the relation between colour and composition in the biotites. The numbered spots refer to the biotites of this paper; the X represents the biotite from a quartz-muscovite-biotite schist from north-eastern Victoria (Tattam, 1929).

The lowest grade biotite (1) has a notably higher Fe^{+++} content than the other metamorphic biotites; its brown, slightly greenish colour contrasts with the reddish-brown of the other samples. The refractive index γ is variable, but the lowest grade mica has the highest γ.

According to Hayama (1959) the change in colour of biotites from green through greenish-brown and brown to reddish-brown is related to a decrease in the ratio $Fe_2O_3/Fe_2O_3 + FeO$ and/or an increase in the TiO_2 content. Hayama argues that there is a tendency for these chemical variations to take place in a given terrain with increase in metamorphic grade. Tilley (1926), also noting similar colour changes in biotites, suggested that the FeO content of biotites from certain metamorphosed areas may increase with increase in metamorphic grade. There is general agreement with Hayama's conclusions regarding the relation between colour and compositional variations, but our biotites consistently fall outside the appropriate colour fields on Hayama's chart (fig. 1). The biotite analysed by Tattam (1929) from a quartz-muscovite-biotite schist in north-eastern Victoria was probably red-brown in colour; if so, it too falls outside the appropriate field in Figure 1.

In assessing chemical variations in the biotites of various metamorphic grades we must consider the relation between the compositions of the hosts and those of the

biotites, the extent of chemical variability in the hosts, and the influence of mineral reactions within the hosts.   In a given rock we may expect that the biotite will accommodate, *inter alia*, Al, Mg, Fe^{+++}, Fe^{++}, Ti, Mn and K.   Most pelitic schists have an excess of Al over $Fe + Mg$ which leads to the development of other aluminous phases in addition to the biotite at appropriate grades.   Such is certainly the case here.   It can be seen from Figure 2 that the biotites have distinctly lower proportions of Al_2O_3 than their host rocks.   Biotites must share the Al_2O_3 available with muscovite and, in the higher grades, with andalusite and cordierite as well.   What effect the development of
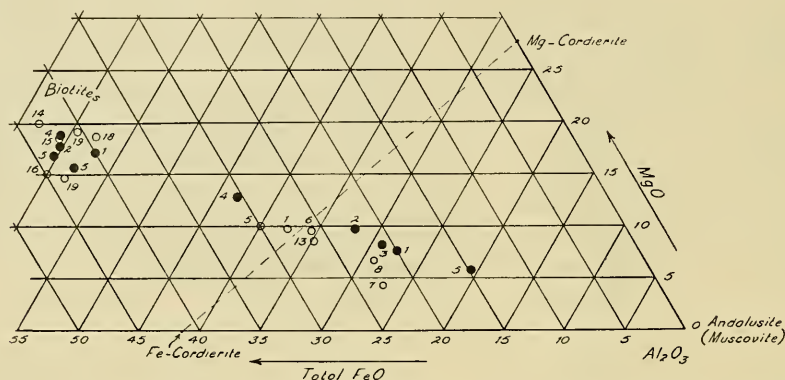

Figure 2.   Portion of the diagram $MgO - Al_2O_3 -$ total FeO showing the relation between composition of biotites and the composition of the host rocks.   The spots represent the analysed biotites and rocks of this paper; the open circles refer to data published by Snelling (1957). Snelling's host-biotite pairs are 1-14, 5-16, 6-15, 7-18, 8-17 and 13-19.

andalusite and cordierite has on the Al content of biotite is not clear, although biotite (1) from a rock without these minerals is the most aluminous of the group.   Each of the pelitic biotites, however, contains important amounts of Al in both Z- and Y-groups of the formula $X_2Y_6[Z_8O_{20}](O.OH.F)_4$ as can be seen in Table 2.

TABLE 2.

Pelitic Biotites.

		This Paper.			Miyashiro (1958).	Snelling (1957).
	1	2	3	Mean.	Mean.	Mean.
Si in Z group	5·41	5·49	5·24	5·38	5·37	5·24
Al in Z group	2·59	2·51	2·76	2·62	2·63	2·75
Al in Y group	0·99	0·82	0·73	0·84	0·73	0·76
Total Y group	5·26	5·53	5·71	5·50	5·56	5·56

Snelling (1957) has suggested that with increase in grade there is an increasing degree of replacement of Al for Si in the Z-group of biotites from Deeside.   Certainly, in the present case, the high-grade biotite (3) has a higher content of Al in the Z-group than do the lower grade biotites.   It must be admitted, however, that the evidence for increasing substitution of Al for Si with increase in grade is not especially convincing. The variation in the Si/Al ratio of the analysed metasediments (pelites, psammopelites and psammites) from the Wantabadgery-Adelong-Tumbarumba area is a feature of original composition dependent mainly on the sand/clay ratio of the original rocks. Although there are only slight differences in the Si/Al ratios of the rocks (1), (2) and (3) from which biotites were separated, Snelling's biotites come from rocks representing a wider range of Si/Al.   The close association of the points representing analysed biotites in Figure 3 is noteworthy.

Figure 4 indicates a rough constancy in the MgO/total FeO ratios of the host rock–biotite pairs. In the absence of other ferromagnesian minerals, $mg*$ (biotite) will approximate mg (rock). Some fifty chemical analyses of metasediments of various grades are available from north-eastern Victoria and south-eastern New South Wales.

Figure 3. $SiO_2 - Al_2O_3 -$ total FeO + MgO diagram showing the relation between biotites and their host rocks. The spots refer to the analyses in this paper, the crosses represent other analysed metasediments from the Wantabadgery-Adelong-Tumbarumba district (Vallance, 1953a). Biotites and host rocks from Deeside (Snelling, 1957) are indicated by open circles. Important phases which may co-exist with biotite in the present area are plotted on the diagram.

Although there is a considerable range in mg values, no systematic variation with grade is evident (fig. 4—based on examples from N.S.W.; the Victorian rocks are as yet unzoned). Higazy (1954) has noted an over-all constancy of the ratio Fe/Mg in the
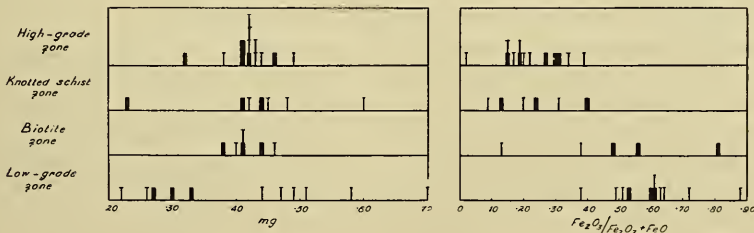

Figure 4. Diagram showing the relations between metamorphic grade and the mg and $Fe_2O_3/Fe_2O_3 + FeO$ values of metasediments from the Cooma, Albury and Wantabadgery-Adelong-Tumbarumba districts of New South Wales. The thick lines represent analysed rocks from the latter area.

rocks of Deeside ranging from chlorite to sillimanite zones; Snelling's (1957) results, also on rocks from Deeside, indicate much the same state of affairs. In such cases, it is reasonable to suppose that, if biotite is the sole ferromagnesian mineral present, variations in mg (biotite) will reflect variations in bulk composition and we can hardly

---

* Niggli value—derived from MgO/FeO + MnO + MgO.

expect to find systematic changes in mg (biotite) with variation in metamorphic grade. However, in the Buchan type of metamorphism, cordierite is a possible phase in pelitic rocks, while in the Barrovian sequence almandine and staurolite may appear. Biotite co-existing with cordierite may be expected to have a lower mg value than the host (analysed examples are given by Mathias (1952) and Hietanen (1956); the opposite relation should hold where biotite co-exists stably with almandine or staurolite (see, for example, Pawlica (1919)). There may thus be contrasting patterns in mg variations in the two zonal sequences. The differences between host and biotite in the two sequences may, however, be relatively small. Figure 2 shows the relations between the biotite—host pairs listed in Table 1, together with the pairs described by Snelling. If lines are drawn from the apex Al_2O_3, through the points representing the host rocks, and extended to the opposite side of the triangle, it will be seen that each of the biotites from rocks containing cordierite falls on the "Fe" side of the appropriate line whilst those biotites from almandine or staurolite-bearing schists fall on the "Mg" side of the line. Presumably these differences are connected with the redistribution of material during the development of new mineral phases. Biotite (1), from a muscovite-biotite phyllite, is relatively more magnesian than its host; it should be noted that this rock contains accessory iron oxide minerals. The appearance of cordierite in the knotted schist zone is apparently associated with the change to a less magnesian biotite. In this case MgO and FeO must be regarded rather as separate components; the four components K_2O, Al_2O_3, $(MgFe)O$, $(FeMg)O$ lead to the assemblage muscovite, biotite, andalusite, cordierite in the knotted schist zone.

The TiO_2 contents of the analysed biotites appear to increase with increase in grade. This may, however, be more apparent than real. No sign of systematic variation in TiO_2 content with metamorphic grade is evident in the analyses of metasediments from the Cooma, Albury or Wantabadgery-Adelong-Tumbarumba districts. As most of the TiO_2 contained in these rocks occurs in the biotite it seems reasonable to expect that those rocks with the highest TiO_2 will carry biotites richest in TiO_2. In the present case, the hosts have TiO_2 (wt. %) 0·56 (1), 0·77 (2), 0·85 (3), and so the apparent increase in TiO_2 in the biotites may well be connected with the sampling. The development of phases such as cordierite, almandine or staurolite would have little effect on the distribution of TiO_2 since these minerals have slight tolerance for Ti-substitution. Snelling's data on the Deeside biotites indicate no systematic variation in TiO_2 content with grade. The pelitic biotites of the Gosaisyo-Takanuki district (Central Abukuma Plateau, Japan) show a rough tendency to have higher TiO_2 contents in the high-grade zone (Miyashiro, 1958), but in the absence of analyses of the individual host rocks it is difficult to establish the significance of this variation.

Miyashiro has also drawn attention to the fact that in his area the biotites of the high-grade zone are poorer in MnO than the biotites of a lower grade zone. The difference in Mn content is attributed to changes in equilibrium relations between biotites and co-existing Mn-bearing garnets. In the present cases garnets are absent, but it seems likely that the Mn of the rock will be shared between biotite and cordierite. Analyses of co-existing cordierites and biotites given by Mathias (1952) and Hietanen (1956) indicate, in each case, that the MnO content of the cordierite exceeds that of the biotite. It must be admitted, however, that the analytical results in Table 1 give no clear picture as to the distribution of Mn. The rock having the highest content of cordierite (no. 3) has a biotite with a substantially higher MnO content than those of the other pelites. All that can be said here is that the pelite with the highest MnO has the most manganiferous biotite.

On the other hand, the oxidation state of iron does show signs of systematic variation. It may be seen from Figure 4 that the higher grade rocks have generally lower $Fe_2O_3/Fe_2O_3 + FeO$ values than their lower grade equivalents. A similar tendency is apparent in the analysed biotites (1), (2) and (3). The highly ferric low-grade biotite (1) is especially noteworthy. Biotites with high Fe^{+++} contents have also been

recorded from low-grade rocks in Scotland (Dalradian Green Beds—Phillips, 1930) and Japan (Miyashiro, 1958; Shidô, 1958). The pelitic and psammopelitic rocks from Deeside of which analyses are quoted by Higazy (1954) and Snelling (1957) give little indication of a declining $Fe_2O_3/Fe_2O_3 + FeO$ ratio with increasing grade. In the case of the biotites described by Snelling there appears to be only slightly more evidence of this relation. At any rate, the values of $Fe_2O_3/Fe_2O_3 + FeO$ for Snelling's biotites are distinctly lower than those of the pelitic biotites listed in Table 1. From Dutchess County, New York, Barth (1936) noted a reddish-brown biotite with little Fe^{+++} from a pelite occurring near the biotite isograd in a Barrovian succession. On the evidence available it seems that the biotites of low-grade pelites in the Buchan type of environment tend to have higher values for $Fe_2O_3/Fe_2O_3 + FeO$ than do those in the biotite zone of a Barrovian sequence. In the higher grade zones the situation is less clear, though the tendency mentioned may well be general.

Miyashiro (1958) and Hayama (1959) have discussed the change in oxidation-state of iron in pelitic/psammitic biotites. The oxidation-state will vary according to the physical environment of metamorphism—temperature, solid-pressure and O_2-pressure being important factors. Miyashiro and Hayama suggest that the O_2-pressure is determined mainly by the dissociation of water. There would thus be a tendency for higher values of $Fe_2O_3/Fe_2O_3 + FeO$ associated with metamorphism under higher water-pressures. Both Miyashiro and Hayama compare Snelling's biotites with samples from the Abukuma Plateau of Japan and conclude that the Barrovian metamorphism took place under lower water-pressures than those prevailing during the Abukuma meta-morphism. The $Fe_2O_3/Fe_2O_3 + FeO$ ratios of the biotites from the Wantabadgery-Adelong-Tumbarumba district are much closer to those from the Abukuma Plateau than to those from Deeside. Tattam's biotite from a metasediment in Victoria has an oxidation-ratio of iron (0·23) within the range of values for the pelitic biotites in Table 1. These relations are noteworthy in view of the fact that the metamorphism in the Australian and Japanese examples is of the Buchan type in contrast to the Barrovian metamorphism of Deeside. It is especially unfortunate that there is no information available on the biotites of pelitic schists in Banffshire. The values of (OH) in the calculated formulae for the biotites (1), (2) and (3) are, in order of increasing metamorphic grade, 4·049, 3·902 and 3·702. No information is available on the relation between the ratio F/OH and grade of metamorphism.

Biotites from Plutonic Rocks.

The biotites (5) and (4), separated respectively from a representative sample of the Wantabadgery Granite and a biotite-rich inclusion from a granodioritic phase of that body, are generally similar in composition and optical characters to samples (2) and (3) from metasediments. The inclusion has a medium-grained, almost granitic, fabric, but contains sillimanite and is probably of sedimentary origin. In contrast, however, to the local metasediments with comparable SiO_2 contents the inclusion holds greater quantities of Na_2O and CaO, possibly derived from the granitic host. Although Na_2O and CaO do not contribute substantially to the composition of common biotites, it should be noted that biotite (4) from the inclusion carries greater amounts of these constituents than the pelitic biotites. The Fe/Mg ratio of the inclusion is similar to those of the analysed pelites, but the total $FeO + MgO$ is considerably greater in the inclusion (see fig. 2). The granite (5) also carries iron and magnesia in similar relative proportions, but the total ferromagnesian content of the granite is, of course, much lower. Figure 2 indicates the richness of the granite in Al_2O_3 relative to total $FeO + MgO$. The biotite from the granite, reflecting this compositional feature, is richer in Al_2O_3 than that from the inclusion. As is to be expected in a rock rich in K-feldspar, the ratio K_2O/Al_2O_3 is higher for the granite than for the pelitic metasediments. Of the five analysed micas, that from the granite has the highest K_2O content. Both plutonic biotites have higher values for the X-group (K, Na, Ca) of the structural formula than the biotites from pelites. In this regard there appears to be a connection between

G

composition of the biotite and composition of the host rock. As the mg values for these plutonic rocks are similar to those of the metasediments quoted here it is not surprising that mg of the biotites should also be roughly similar. It is not clear, however, why the granitic biotite should appear to be slightly less magnesian than the host rock. The relatively high MnO content of biotite (4) from the inclusion is presumably a reflection of the high MnO content of the host.

Nockolds (1947) has collected data on the relation between paragenesis and chemical composition of biotites in granitic rocks. Referring to the information collected by Nockolds it may be seen that there are differences in the distribution of Al in the Z- and Y-groups of the structural formulae of biotites according to the nature of the minerals associated with the dark micas. In the present case muscovite occurs with biotite in both granite and inclusion; sillimanite is present in both cases, though in the granite it is a minor accessory. The biotites from these rocks have their Al distributed in proportions similar to those of Nockolds' biotites associated with muscovite (see Table 3). For comparison, the distribution of Al in two plutonic biotites from north-eastern Victoria is given in Table 3. The rock from which Tattam separated his biotite no. 16 appears to have contained muscovite; biotite no. 15 was from an inclusion lacking muscovite in a granite body. It can be seen from Table 2 that the biotites from metamorphosed pelites, in which muscovite consistently appears, have their Al distributed in a manner comparable with that of the biotites of plutonic rocks containing muscovite.

<div align="center">

TABLE 3.

Plutonic Biotites.

</div>

		This Paper.		Tattam (1929).		Nockolds (1947).	
		4	5	(16)	(15)	(a)*	(b)
Si in Z group	.. ..	5·30	5·43	5·34	5·33	5·26	5·43
Al in Z group	.. ..	2·70	2·57	2·66	2·64	2·74	2·57
Al in Y group	.. ..	0·74	0·91	0·62	0·17	0·78	0·40
Total Y group	.. ..	5·86	5·50	5·36	5·44	5·42	5·61

* (a) refers to mean values for biotites associated with muscovite in rocks ranging from granites to quartz-diorite.
   (b) refers to mean values for biotites " occurring alone " in rocks ranging from granites to tonalite.

The oxidation-ratios of iron in the plutonic biotites are of the same order as those in the biotites of the higher grade metasediments. From this it might be suggested that water-pressures were roughly equivalent in both the high-grade metamorphic and plutonic environments. If such were the case there is at least no conflict with the field and petrographic evidence (Vallance, 1953a, b) suggesting a close relation in time and in the physical conditions under which the metamorphism was accomplished and the granite locally introduced and crystallized. The forty biotites from granites, adamellites, granodiorites, tonalites, quartz diorites and diorites quoted by Nockholds (1947) have an average $Fe_2O_3/Fe_2O_3 + FeO$ ratio of 0·17. In terms of paragenesis there appears to be little significant variation in the oxidation-ratio of the iron. Thus of the seven biotites occurring with muscovite, the average ratio is 0·18 and the range 0·08–0·36; sixteen biotites occurring alone have an average of 0·16 and a range of 0·07–0·34; while seventeen biotites associated with hornblende have values ranging from 0·04–0·29 with an average of 0·19. In comparing these values with those of the present samples it must be remembered that Nockolds' biotites represent a wide sampling of plutonic environments. The biotites (4) and (5) have values for $Fe_2O_3/Fe_2O_3 + FeO$ very close to the average based on Nockolds' collection.

<div align="center">

Granites and Metamorphism in Buchan and Barrovian Environments.

</div>

If, in the present case, water-pressures were of the same order in both higher grade metasediments and in the granitic environments it is interesting to speculate on this

association in relation to the Buchan-type metamorphism. The suggestion was made earlier, following the arguments of Miyashiro and Hayama, that the metamorphism was accomplished under rather higher water-pressures than those obtaining during the Barrovian metamorphism in Deeside. Not much information is available on the granites and granitic biotites associated with the Deeside metamorphism. Barrow (1893) published a partial analysis of one biotite from an Older Granite. This biotite, though less magnesian ($mg = 0.25$) than the biotites from metasediments quoted by Barrow (1893) and Snelling (1957). is, on the whole, fairly similar in composition to the pelitic biotites. The value of $Fe_2O_3/Fe_2O_3 + FeO$ for Barrow's granitic biotite (0.11) is well within the range ($0.03-0.20$; average 0.10) of values for the biotites from metasediments of the almandine and higher grade zones in which the Older Granites are emplaced in the Deeside region. The evidence, such as it is, suggests lower oxidation ratios for iron in the biotites of both metasediments and plutonic rocks of the Barrovian association when compared with the biotites of higher grade pelites and plutonic rocks of the present case. This difference is also to be seen in the oxidation-ratios of iron in the plutonic rocks of the two areas. Williamson (1935) gives analyses of three samples of an Older Granite (Duchray Hill Gneiss) from Glen Shee, adjacent to Deeside. The range of values for $Fe_2O_3/Fe_2O_3 + FeO$ in Williamson's examples is $0.09-0.20$ (average 0.14). From the Wantabadgery, Cooma and Albury districts of New South Wales, we have seven analysed samples of granitic rocks associated with the Buchan-type metamorphism; the range of $Fe_2O_3/Fe_2O_3 + FeO$ for these cases is $0.14-0.46$, with an average value of 0.22. No firm conclusions can be based on evidence such as this, but certainly the nature of the granitic rocks (which may be, in part, migmatitic) associated with these two types of regional metamorphism is a matter deserving of close attention. In both cases it seems evident from field and chemical studies that the granitic rocks are derived largely from materials in the metamorphosed terrain. Most, if not all, of the iron and magnesium of the plutonic rocks may have been supplied from the metasediments. The average mg values for thirty-seven metasediments from Cooma, Albury and the Wantabadgery-Adelong areas is 0.42; the average mg for the seven associated granitic rocks is 0.38. Within the latter area, the similarity is more striking; for fourteen metasediments the average mg is 0.37, while four analysed granitic rocks also give an average mg of 0.37. Comparisons such as these involve, of course, the assumption that the analysed rocks constitute really representative samples. For twenty-one analysed metasediments from Deeside and Glen Shee (Barrow, 1893; Higazy, 1954; Snelling, 1957; Williamson, 1935) the average mg is 0.36; the average for Williamson's Older Granite is 0.37.

Fyfe, Turner and Verhoogen (1958—fig. 108) suggest that the Buchan and Barrovian environments differ in that the Buchan metamorphism is accomplished under conditions of lower load pressure (lower depths) than the Barrovian metamorphism. The temperature range, on the other hand, may be of the same order in both cases. As yet we know little about the influence of stress on the mineralogy of the rocks produced in the two environments. Harker (1939) suggested that the Buchan-type metamorphism is effected under conditions of lower stress than those associated with a Barrovian metamorphism. It seems likely from the present study, as well as from the observations of Japanese workers, that water-pressures are higher in metamorphism of the Buchan type. Both regional metamorphic sequences lead to the development of migmatitic and granitic rocks which apparently bear the impress of the physical environments appropriate to the higher grades of metamorphism in the two cases.

References.

BARROW, G., 1893.—On an intrusion of muscovite-biotite gneiss in the south-east Highlands of Scotland. *Quart. Jour. Geol. Soc. London,* 49 : 330-358.
————, 1912.—On the geology of lower Deeside and the southern Highland border. *Proc. Geol. Assoc.* (London), 23 : 268-284.
BARTH, T. F. W., 1936.—Structural and petrologic studies in Dutchess County, New York. Part II: Petrology and metamorphism of the Paleozoic rocks. *Bull. Geol. Soc. Amer.,* 47 : 775-850.

FYFE, W. S., TURNER, F. J., and VERHOOGEN, J., 1958.—Metamorphic reactions and metamorphic
    facies. *Geol. Soc. Amer., Memoir 73.*

GROVES, A. W., 1951.—*Silicate Analysis.* 2nd edition. London. Allen and Unwin.

HARKER, A., 1939.—*Metamorphism.* 2nd edition. London. Methuen.

HAYAMA, Y., 1959.—Some considerations on the color of biotite and its relation to metamorphism.
    Jour. Geol. Soc. Japan, 65 : 21-30.

HIETANEN, A., 1956.—Kyanite, andalusite, and sillimanite in the schist of Boehls Butte
    quadrangle, Idaho. *Amer. Mineral.,* 41 : 1-27.

HIGAZY, R. A., 1954.—A geochemical study of the regional metamorphic zones of the Scottish
    Highlands. *Congr. geol. Intern., XIX Session* (Algiers), *C.R.,* 15 : 415-430.

HOWITT, A. W., 1888.—Notes on certain metamorphic and plutonic rocks at Omeo. *Proc. Roy.
    Soc. Victoria,* 24 : 100-131.

JOPLIN, G. A., 1942.—Petrological studies in the Ordovician of New South Wales. I. The Cooma
    Complex. PROC. LINN. SOC. N.S.W., 67 : 156-196.

————, 1947.—Idem. IV. The northern extension of the north-east Victorian metamorphic
    complex. *Ibid.,* 72 : 87-124.

MATHIAS, M., 1952.—An unusual cordierite-rock from Upington, Cape Province. *Mineral. Mag.,*
    29 : 936-945.

MIYASHIRO, A., 1958.—Regional metamorphism of the Gosaisyo-Tankanuki district in the
    Central Abukuma Plateau. *Jour. Fac. Sci., Univ. Tokyo,* Sec. II, 11 : 219-272.

NOCKOLDS, S. R., 1947.—The relation between chemical composition and paragenesis in the
    biotite micas of igneous rocks. *Amer. Jour. Sci.,* 245 : 401-420.

PAWLICA, W., 1919.—Garluchowskie skaly wapiennokrzemianowe. *Rozpr. Matem.-Przyrodn.
    Akad. Umiejetnosci* (Cracow), Ser. III, 18 (for 1918), A, 21-67.

PHILLIPS, F. C., 1930.—Some mineralogical and chemical changes induced by progressive
    metamorphism in the green bed group of the Scottish Dalradian. *Mineral. Mag.,* 22 : 239-
    256.

READ, H. H., 1952.—Metamorphism and migmatisation in the Ythan Valley, Aberdeenshire.
    Trans. Edinburgh Geol. Soc., 15 : 265-279.

SHIDÔ, F., 1958.—Plutonic and metamorphic rocks of the Nakoso and Iritôno districts in the
    Central Abukuma Plateau. *Jour. Fac Sci., Univ. Tokyo,* Sec. II, 11 : 131-217.

SNELLING, N. J., 1957.—Notes on the petrology and mineralogy of the Barrovian metamorphic
    zones. *Geol. Mag.,* 94 : 297-304.

TATTAM, C. M., 1929.—The metamorphic rocks of north-east Victoria. *Geol. Surv. Victoria,
    Bull. 52.*

TILLEY, C. E., 1925.—Metamorphic zones in the southern Highlands of Scotland. *Quart. Jour.
    Geol. Soc. London,* 81 : 100-112.

TILLEY, C. E., 1926.—On some mineralogical transformations in crystalline schists. *Mineral.
    Mag.,* 21 : 34-46.

VALLANCE, T. G., 1953a.—Studies in the metamorphic and plutonic geology of the Wantabadgery-
    Adelong-Tumbarumba district, N.S.W. Part I. Introduction and metamorphism of the
    sedimentary rocks. PROC. LINN. SOC. N.S.W., 78 : 90-121.

————, 1953b.—Idem. Part III. The granitic rocks. *Ibid.,* 78 : 197-220.

WILLIAMSON, W. O., 1935.—The composite gneiss and contaminated granodiorite of Glen Shee,
    Perthshire. *Quart. Jour. Geol. Soc. London,* 91 : 382-422.